JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

PERFORMANCE EVALUATION OF STABILIZED SOIL FOR LOW VOLUMEPAVEMENTS

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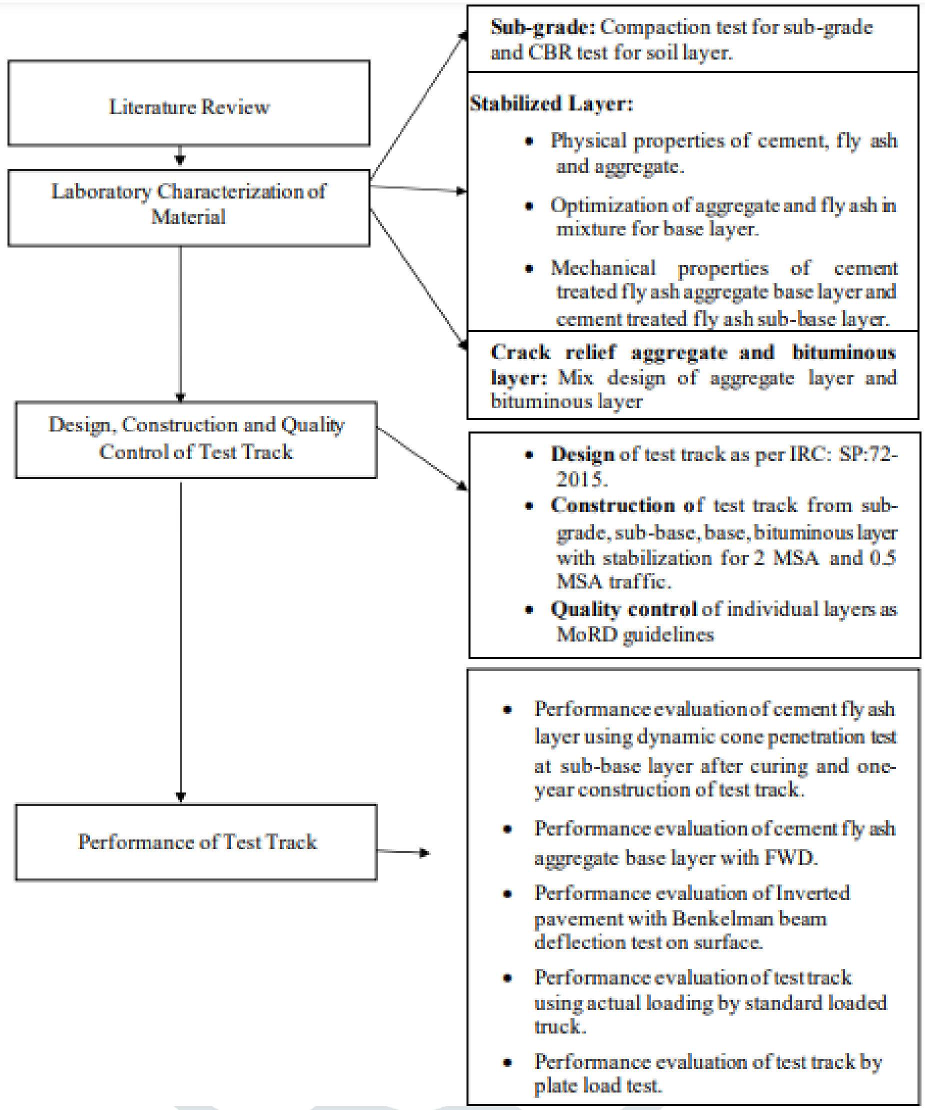
Abstract:The primary purpose of a pavement is to offer a smooth and secure surface for traffic, while efficiently supporting the intended loads, regardless of weather conditions. Flexible pavement is composed of designed layersof natural or processed materials that are placed on top of the sub-grade, which is the layer of soil beneath. The main purpose is to equally disperse the vehicular loads delivered to the soil sub-grade, within permitted limits. The objective of a pavement construction should be to have a surface that offers a suitable level of ride quality, sufficient skid resistance, favorable light-reflecting properties, and minimal noise pollution. The objective is to ensure that the stresses transferred by wheel loads are adequately diminished so as not to surpass the minimum necessary bearing capacity of the soil sub-grade.

Introduction: Flexible pavements transfer wheel load stresses onto the lower layers of granular natural materials by grain-to-grain contact at the point of contact. The stress resulting from the load of the wheel on the upper surface of the pavement is spread out across a larger area, leading to a decrease in stress as the depth increases. The flexible pavement is designed to exploit the stress distribution features, which results in the presence of multiple layers. Therefore, flexible pavement design employs a stratified structure, allowing for the construction of the pavement in multiple layers. Conversely, the uppermost layer must possess sufficient strength (using the highest grade material) to endure the highest amount of compressive stress, including the effects of deterioration over time. The lower layerswill be subjected to reduced stress levels, allowing for the use of lower quality materials. Figure 1.1 below displays a standard flexible pavement consisting of various layers.Flexible pavements are built using a variety of natural materials that are either bound or unbound. Materials that are bound together with bitumen can take the form of either thin surfaces, typically used for low volume roads, or dense bituminous concrete surface courses, typically used for high volume roads. Flexible pavement layers transmit the deformations of the lower layers to the surface layer, meaning that any undulations in the sub-grade layer are transferred to the top surface layer. The design life and performance of flexible pavement are determined by the stresses generated primarily by wheel load, which must be significantly lower than the allowed stresses of each layer. These stressors are influenced by various factors, as listed below:The factors that affect the performance of a structure under traffic load include contact pressure, wheel load, configuration, moving loads, and load repetitions. The material properties of each layer also play a significant role. Additionally, environmental factors such as temperature and precipitation need to be considered. The type of analysis conducted can be either linear elastic or non-linear, such as viscoelastic or stress-dependent layer analysis. Figure 1 illustrates a common representation of the distribution of load between individual grains in a flexible pavement system.In order to thoroughly examine the many aspects of pavement performance, it is important to take into account three specific types of pavement damage that occur as a result of recurrent traffic loads. These types of damage are commonly referred to as pavement distress and are illustrated in Figure1.3.

Methodology:Approach The primary aim of the research study is to assess the efficacy of inverted pavement for low-volume roadways. In pursuit of this objective, a comprehensive literature review pertaining to the research issuehas been carried out and documented in chapter 2. Subsequently, the laboratory has concluded the final mix design for the base and sub-base layer of an inverted pavement including fly ash. Prior to the actual construction of the test section, the material qualities necessary for construction were identified. These properties include sub-grade compaction properties, sub-base compaction properties, base layer compaction properties, aggregate layer compaction properties, and bituminous layer properties. In addition, the specific structure of 2 million standard axles (MSA) and 0.5 MSA traffic has been completed. The construction of the test track was finished in accordance with IRC SP: 72:2015 and the requirements set by the Ministry of Rural Development (MoRD). Subsequently, the test track was evaluated at various levels: the stabilised sub-base level was assessed using the dynamic cone penetration (DCP) test, the stabilised base level was evaluated using the falling weight deflectometer (FWD) test, the surface level was examined using the Benkelman Beam

Deflection (BBD) test, and the Plate Load Test was conducted. Ultimately, the test track's true performance was evaluated by implementing the genuine loading conditions using a mobile vehicle. The flowchart illustrating the same information may be found on the following page.



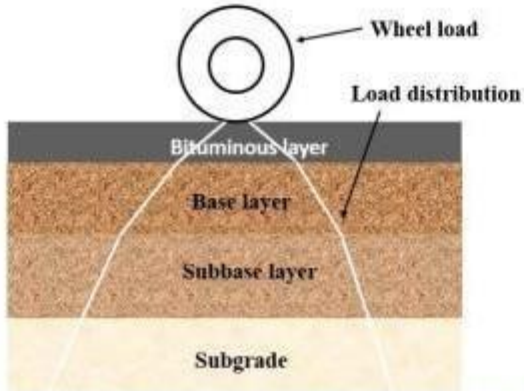


Figure 1.1:Typical Load Distribution in Flexible Pavement

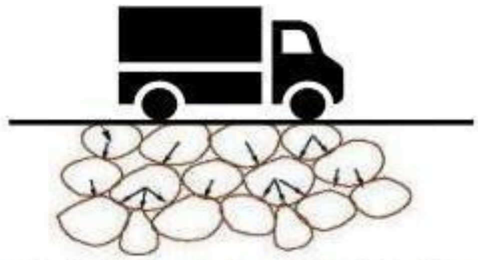


Figure 1.2:Grain to Grain Load Distribution

Figure 1.3: Critical Locations of Stresses and Strains in Flexible Pavements

Uses of response in the analysis of critical locations in a pavement structure have been given in Table 1.1.

Table 1.1: Critical Locations of Response in Flexible Pavement

Location	Response	Type of Use
Pavement Surface	Deflection	Used in imposing load restrictions
Bottom of HMA layer	Horizontal Tensile Strain	Used to predict fatigue failure in the bituminous layer
Top of Sub-grade	Compressive Strain	Used to predict rutting failure in the pavement due to the combined effect of all the layers

Literature ReviewIntroduction This chapter provides a comprehensive overview of the existing studies through a literature review. The literature mostly examines inverted pavement systems and their specific composition, which includes a bituminous layer, aggregate layer, cement-treated base layer, cement treated sub-base layer, and sub-grade. The characteristics of each layer that impact the performance of the pavement system have also been addressed. This chapter discusses the economic advantages of using inverted pavement, the problem of fly ash waste utilisation, and identifies gaps in the current understanding.Inverted Pavement Systems refer to a type of pavement system where the traditional layers of pavement are reversed or inverted. An inverted pavement system refers to an alternative method of constructing pavements. The practice was initially implemented in South Africa during the 1950s, entailing the creation of robust crushed stone foundation layers atop stabilised subbase layers. The individuals responsible for the construction of crushed stone base layers used in South African inverted pavements are commonly referred to as "G1" base layers (Horne, 1997; Jooste et al., 2005; De Beer, 2012). Inverted pavements, also known as stone interlayer pavements, G1-base pavements, inverted base pavements, sandwich pavements, and upsidedown pavements, arereferred to as such by Lewis et al. (2012). Overall, the stone interlayer test portion has exhibited satisfactory performance. The materials utilised in an inverted pavement system are identical to those employed in a normal pavement, with the main difference being the rearrangement of the material layers. An inverted pavement consists of a thin layer or layers of hot mix asphalt (HMA), an unbound aggregate base (UAB) layer, a cement-treated base (CTB), and a sub-base layer. These layers are placed on a prepared subgrade. In a flexible pavement system, the UAB layer is often positioned above the sub-base, while thicker HMA layers are added on top. In an inverted pavement design, a Cement Treated Base (CTB) layer is placed on the prepared sub-base or subgrade. On top of the CTB layer, an Unbound Aggregate Base (UAB) layer is laid, followed by one or more Hot Mix Asphalt (HMA) layers. Typically, the system is composed of the following components: • The HMA layer is typically between 2 to 3.5 inches thick (50mmto 75mm), while in South Africa it is commonly limited to less than 2 inches of HMA cover. The UAB layer should have a thickness of 6 to 8 inches (150mm to 200mm) and should be compacted to a minimum density of 100% modified proctor density. The CTB layer has a thickness ranging from 6 to 12 inches (150mm to 300mm) and has around 4% cement content (Buchanan, 2010). Figure 2.1 depicts the arrangement of layers in a standard inverted pavement structure. The distribution of stress and strain in an inverted pavement differs from that of a flexible pavement, as indicated in Table 1.1. The horizontal tensile strain at the bottom of the cement stabilised foundation layer must fall within acceptable thresholds.

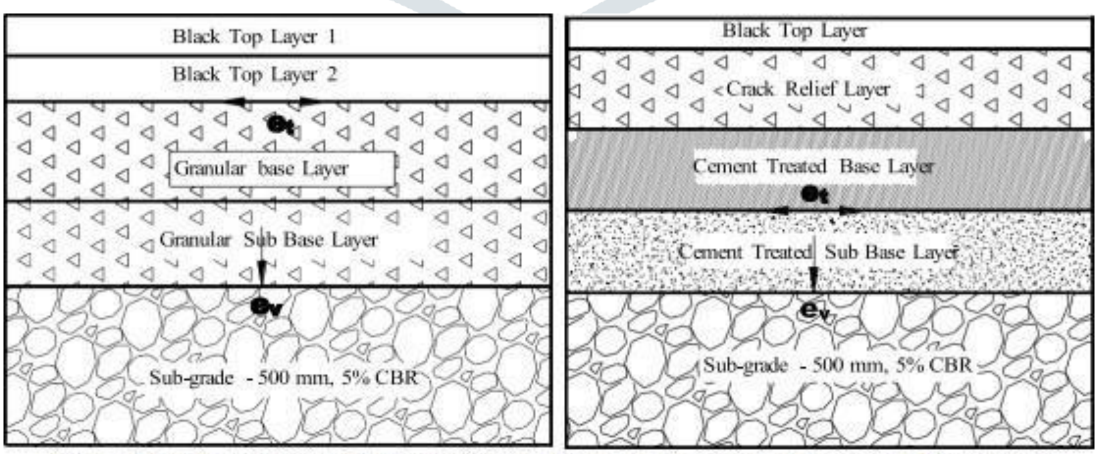


Figure 2.1:Pavement Composition of Conventional and Inverted Pavement

Table 2.1:Recommended Values of Resilient Modulus of Aggregate Layer over Uncracked Cement Treated Layer (IRC:37-2012)

Material	Modulus over uncracked cement-treated layer (MPa)	Recommended modulus (MPa)	Poisson's ratio
High quality graded crushed rock as WMM	250-1000	450	0.35
Graded Crushed stone and soil binder; fines PI < 6	200-800	350	0.35
Natural gravel; PI < 6, CBR > 80 Fines PI<6	100-600	300	0.35

Note: WMM-Wet Mix Macadam, PI-Plasticity Index, CBR- California Bearing Ratio

Table 2.2:Different stress-dependent model used in the design

Equation	References	Comment
$M_r= K_1\times\theta^{K2}$	Hick and Monismith, 1971	K_1, K_2, K_3 and K_4 are regression model constants that could be obtained from material properties.
$M_r= K_3\times\sigma_d^{K4}$	Boyce et. al., 1976	
$M_r=K_1\times\theta^{K2}\times\sigma_d^{K3}$	Uzan, 1985	
$Mr=K_1p_a(\frac{\theta}{pa})^{K2}(\frac{\tau oct}{pa})^{K3}$	Witczack and Uzan 1988	
$Mr=K_1p_a(\frac{\theta}{pa})^{K2}(\frac{\tau oct}{pa}+1)^{K3}$	AASHTO, 2008	

. Utilising a hydraulic compressive strength apparatus, the evaluation is conducted. The UCS values of CTB after seven days of curing that are routinely utilised in international literature are shown in Table 2.3 below. It is important to note that the necessary UCS is highly dependent on the kind of road and material.

Table 2.3:UCS Requirement of Cement Treated Layer

Type of Material	Strength in terms of UCS
Sand and gravelly	2.06-4.14 MPa (300-600 psi)
Aggregate Base course	5.17 MPa (750 psi)
Fly mix base course	2.757 MPa (400 psi)
Base course	5.17 (750 psi) U.S. Corps of Engineers
CTB	2.06-5.515 MPa (300-800 psi)
Road base	2.93-5.99 MPa (435-870 psi)
Cement stabilized sand clay gravel	3.447 MPa (Minimum-500 psi)
Base Course (South Africa)	2.93 MPa (Minimum-435 psi)
Base course (United Kingdom)	2.5-4.5 MPa (363-653 psi)
Base course (Australia)	>3MPa (Austoroad,2010)
Base course (China)	2.93 -4.99 MPa (435-725 psi)
Base course (New Zealand)	2.93 MPa (Minimum-435psi)
Base course	4.14 MPa (600 psi)
Base Course (India)*	4.5-7 MPa (653 psi) (IRC:37-2012)
Base Course (India)*	3.0 MPa (363 psi) (MoRD-2014)
Sub-base Layer (India)*	1.5-3.0 MPa and 0.75-1.5 MPa for Traffic < 10 MSA)
ASTM, cement % in base layer	3-5
AASHTO, cement % in base layer	3-5

Source: Ismail et al, 2014 Note: Not from source

Split strength, compressive resilient modulus, fatigue, and UCS are all material qualities that are strongly correlated with one another. Incorporating waste materials or industrial by-products makes it more productive, and using cement in the base layer and low target UCS helps with that. The maximum compressive strength has been set by several authorities; for instance, the UCS value in Table 2.3 is representative of the generally used values for cement-treated layers.

Table 2.4:Different Cement Stabilized Fatigue Models

S.No.	Model Name	Equation	Parameters in the Equation	Reference
	Strain based model			
1	South Africa Department of Transportation Model	$\log N = 9.1\,[1-\frac{ds\varepsilon_t}{\varepsilon_b}]$	ds = factor to account for shrinkage crack induced stress concentration ε_t=tensile strain ε_b=breaking strain	Freeme et al. (1982)
2	Australian Model	$\log N = 18 \log \frac{C}{\varepsilon_t}$	C = constant, E = modulus of the cemented material ε_t= tensile strain	NAASRA (1987)
3	Australian Model	$\log N = 12 \log[\frac{\frac{11300}{E}^{0.804}+191}{\varepsilon_t}]$	E = modulus of the cemented material ε_t= tensile strain	Austroads (2004)
4	Australian Model	$\log N = 8\log[\frac{35000}{\varepsilon_t E^{0.45}}]$	E = modulus of the cemented material ε_t= tensile strain	Jameson et al. (1992)
5	Literature	log N = -13.178 (σ/S) + 14.394	N is flexural fatigue life, σ is flexural tensile stress, and S is the flexural tensile strength of the specimen	Yu et al. (2011)
	Stress based Model			
6	French Model	$\log N = \frac{1}{B}\,[\,[\frac{ds\varepsilon_t}{\varepsilon_b}]$	B = regression constant ε_b=Breaking strain	Corte (1996)

The assumption that fatigue crack propagation is minimal is commonly made when planning bituminous pavements with cement-treated bases and sub-bases. According to several studies (Austroads 2004, Otte et al. 1992, Theyse et al. 1996), fatigue cracking failure occurs initially in the cement-treated layer, and then, once its fatigue life is spent, the fatigue cracks begin to propagate across the bituminous layer. According to Austroads (2004), the elastic modulus should be one-fifth of the design modulus when the fatigue life of cementitious materials comes to a close. According to (Das and Pandey, 1998), Figure 2.2 displays the modulus fluctuation with design life.

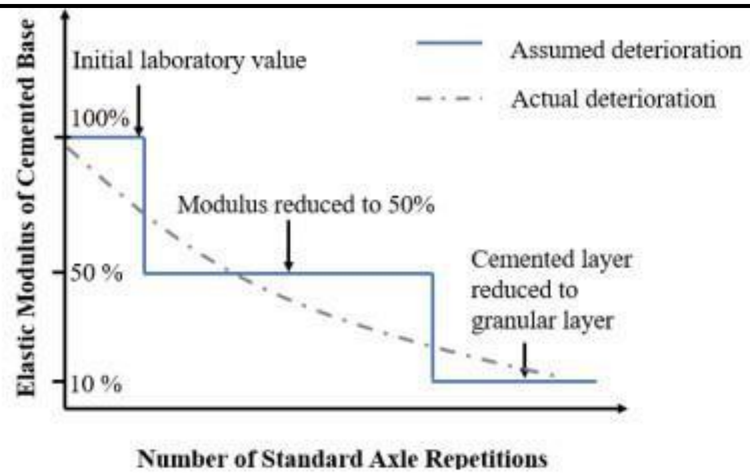


Figure 2.2:Variation of Elastic Modulus of the Cement Treated Layer with Traffic Repetitions

There are three distinct stages to the long-term behaviour of aggregate bases that have been minimally treated with cement, as indicated in Figure 2.2 above. First, there is the phase before cracks form; second, fatigue cracking begins; and third, crushing has progressed. The layer acts more like a slab during the precracked phase, with horizontal plane dimensions being more important than the layer thickness; the elastic modulus at this stage is the same as the one measured right after production. The initial elastic modulus decreases at a quick rate when fatigue cracking begins. In the order of the layer's thickness, the layer separates into big blocks with dimensions in the horizontal plane. Eventually, the layer undergoes a reduction to a granular equivalent in the advanced crushing condition, when blocks are smaller than the thickness of the layer. According to Theyse et al. (1996), the once- cemented aggregate now exhibits nonlinear behaviour and stiffness that is depending on stress. Because the cement- treated foundation layer's mechanical behaviour has changed, the stresses and strains in the pavement as a whole have shifted. An important mode of distress is the degradation of the cement-treated aggregate; nevertheless, this has far-reaching consequences for how other layers of the surface, particularly the asphalt concrete layer, experience anguish over time. In addition, because the cement has a higher elastic modulus, the compressive strain on the subgrade is often modest on an undisturbed segment. According to Theyse et al. (1996), the pavement is thus not at risk of rutting. Surface cracking, maybe caused by fatigue cracks in the cement-treated material, is a likely outcome of using a cement-treated material base with thin bituminous topping. The degree and severity of surface cracking determine the end of life, which is defined conservatively when cement-treated material bases are utilised with thin bituminous surfaces. During the service life of a cement- treated layer, transverse and longitudinal cracks caused by shrinkage and thermal stresses from hydration are common, according to IRC:37-2012, annexure X-7. It is necessaryto cover the cement base with a Stress Absorbing Membrane Interlayer (SAMI) made of elastomeric modified binder in order to prevent reflection cracking. Commercially available geotextile seals and synthetic products feature a mechanism that retards cracks. Any break larger than 3 mm will render SAMI ineffective. Hence, a high-quality aggregate interlayer between the bituminous and cement-treated base layers is another way to stop cracks from spreading to the top bituminous layer. Interlayers made of wet mix macadam (WMM) that adhere to the standardsset by the Ministry of Roads, Transport, and Highways (MoRTH) are suitable. Because it is composed of sand sandwiched between two rigid layers, aggregate exhibits a high modulus layer behaviour under heavy loads and a low modulus layer behaviour under mild loads. Table 2.4 and S. No. 8 from Austroad, 2004 form the basis of the fatigue equation that was adopted in the Indian Road Congress (IRC): 37. Austroad (2014) has more recently, according to their research, suggested keeping the fatigue connection from earlier Austroads (2004) that ties life to the 12th power of applied strain, as stated in IRC:37-2012. A significant revision to the fatigue correlations was suggested by Austroads (2014), however, in 2004 by Austroad. For each applied strain, the older model from 2004 used a flexural modulus as its parameter. Differentiating fatigue properties across materials using only flexural modulus for a given applied strain is not a useful approach. According to thestudy (Austroad, 2014), flexural strength and flexural modulus account for most of the variation in fatigue characteristics. Below are the specific revisions that the Austroad, 2014 suggests should be made to the Austroads, 2004 fatigue equation (Table 2.4, S.No. 3). Assumptive fatigue relationships should be linked to presumptive moduli and strength values; the end of fatigue life should be defined as one-fifth of the design modulus; all cemented materials should retain a strain damage exponent of 12; the current Austroads fatigue relationships should be deleted; a method should be included for determining in-service fatigue relationships from laboratory measurements; a laboratory-field strain shift factor should be included; and an assumed strain damage exponent of 12 should be included.

Table 2.5: Inverted Base Pavements tested by the Heavy Vehicle Simulator

Location	Year	Layer thickness from top to bottom [Height in mm]
S12 Cloverdene C17	1978	Gap-graded asphalt [70] G1 [320] Lightly cemented subbase [280] Natural gravel [100]
P157/1 Olifantsfontein	1980	Semi-gap asphalt [30] G2 [200] Lightly cemented subbase [100] Natural gravel [200]
P157/2 Jan Smuts	1980	Semi-gap asphalt [35] G1 [140] Cemented gravel [255] Natural gravel [125]

Also, the Benkelman beam deflection test of the inverted and conventional pavement has been shown in Table 2.6

Table 2.6: Benkelman Beam Deflection Measurements for the Different Pavements

	Layer thickness [mm]	Deflection (mm)
Inverted Pavements	AC [37.5] UAB 3-6 PI [150] CTB [150] Untreated subbase [89]	0.425
	AC [75] UAB non-plastic [150] CTB [150] Untreated subbase [229]	0.4
	AC [75] UAB non-plastic [150] CTB 4% [150]	0.35
	AC [75] UAB PI:3-6 [150] CTB 4% [150]	0.475
	AC [75] UAB non-plastic [150] Asphalt-treated base [150]	0.425
	AC [75] UAB PI:3-6 [150] Asphalt-treated base [150]	0.45
Conventional Pavement	AC [75] CTB 1.5% [150] Untreated subbase [175]	0.275
	AC [75] CTB 1.5% [150] Untreated subbase [375]	0.375
	AC [75] UAB non-plastic [150] Untreated subbase [375]	0.45
	AC [75] CTB 3% [150] Untreated subbase [375]	0.25
	AC [75] CTB 3% [150] Untreated subbase [175]	0.275
	AC [75] CTB 3% [150] UAB non-plastic [150]	0.475
	AC [75] UAB non-plastic [150] Subbase [250]	0.6
	AC [75] UAB PI:3-6 [150] Subbase [250]	0.6
	AC [75] Asphalt-treated base [150] Subbase [250]	0.425
	AC [75] CTB 4% [150] Subbase [250]	0.375
	AC [75] CTB 2% [150] Subbase [250]	0.425

Source: Santamarina, & Papadopoulos, 2014

Laboratory Material Properties And Pavement Design:Getting Started The laboratory testing of an inverted pavement's various layer systems, in conjunction with pavement design, is detailed in this chapter. Using the strength and durability criteria as a starting point, the process optimises the cement, fly ash, and aggregate in a cement- treated base layer, building upon the basic material attributes of the three. Mix design of stabilised layers (i.e., cement-treated base layer, cement stabilised sub-base layer), bituminous layer properties, and crack relief aggregate layer qualities are also covered in this chapter. At long last, we have the low-volume road's intended inverted pavement design thickness. The effectiveness of inverted pavements, designed for roads with low traffic volumes, is the foundation of the current investigation. Hence, in order to examine the controlled field performance, two different pavement crust compositions were devised, implemented, and created. On the prepared sub-grade for 0.5 million standard axles (MSA) and 2 MSA, the crust composition includes an open graded premix carpet (OGPC), a cement treated aggregate fly ash base layer (CTAFBL), and a cement treated fly ash sub-base layer (CTFSBL). This chapter presents the results of an evaluation of the material qualities employed for each layer of the inverted pavement for both pavement compositions. Last but not least, the chapter details the inverted pavement design for various compositions. The next chapter will cover the details of pavement evaluation and construction. While aggregate, fly ash, and cement make up the foundation layer of the pavement, fly ash and cement are the only ingredients in the sub-base Layer. Before cement was added, the aggregate and fly ash composition was fine-tuned, and the mechanical properties of CTAFBL were further assessed. We have tested the mechanical qualities using the same method as CTFSBL.studies have already analysed the chemical composition of fly ash collected from Dadri (Binod K. et al., 2007; Kaniraj and Gayathri, 2004). Table 3.1 displays the results that were acquired from them.

Table 3.1: Chemical Composition of Fly Ash

Chemical composition	% Composition (1)	% Composition (2)
Silica (SiO_2)	62.54	60.12
Alumina (Al_2O_3)	28.00	30.16
Iron Oxide (Fe_2O3)	4.98	6.36
Lime (CaO)	1.54	1.00
Magnesia (MgO)	0.85	0.53
Others	1.52	0.077
Loss on ignition	0.57	0.40
Total	100	100

Source- 1: Kumar B. et a1 2007; Source 2: Kanirajand Gayathri, 2004

Table 3.2: Physical requirements of Fly Ash as Pozzolona

Sl. No.	Characteristics	Requirements as per IRC SP: 89-2010	Obtained Results
1.	Fineness-specific surface in m^2 /kg by Blaine"s permeability test, min.	250	349
2.	Particles retained on 45 microns IS sieve,max.	40	21
3.	Lime reactivity in N/mm², min.	3.5	4.6
4.	Soundness by autoclave test expansion of specimen in percent max.	0.8	0.02

Based on the researchers' findings, it is easy to assume that fly ash falls into the class-F group (Al2O3+SiO2+Fe2O3 >70%) according to ASTM C 618, since the chemical composition of the source is identical. Afterwards, the fly ash utilised in this study was assessed to see if it was suitable to be employed as a pozzolanic material according to IRC:SP:89-2010. You can see the outcome in Table 3.2.

Results are significantly higher than the minimal need for fineness, lime reactivity, etc., and the pozzolanic property of the fly ash is evident from the properties listed above. Additionally, it was determined that the fly ash utilised had aspecific gravity of 1.98. Table 3.3 displays the fly ash gradation employed in the research investigation.

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Table 3.3: Sieve Analysis of Fly Ash

Sieve size	% cum passing
37.5	100
19	100
0.6	100
0.3	100
0.15	88.7

Conclusion:The base and subbase layer of the pavement are tested for fly ash utilisation to the utmost extent. In the inverted pavement subbase layer, fly ash is used to its fullest extent (100% aggregate replacement), while in the base layer, it is used to a lesser extent (22% aggregate replacement). This application has resulted in a significant reduction of the amount of fresh aggregate used while still satisfying the design requirements set out by the ministry. The thesis also includes information on building, field evaluation, and laboratory use of materials. Inverted pavement's performance on low-volume roads was the focus of this thesis's recommendation. It is recommended to use a percentage of fly ash in cement-treated layers to replace fresh aggregate, as long as it meets the material's mechanical properties according to specifications. Using fly ash in the cement base layer and subbase layer will not compromise the mechanical properties. In addition, fly ash can lessen the heat of hydration in cement-treated layers by 90 degrees, which means that shrinkage cracking is less likely to occur. The crack relief aggregate interlayer, which was supposed to stop the fracture from spreading from the cement-treated base layer to the bituminous layer, has rutted, according to the findings. Rutting is more of an issue with layers of crack relief aggregate that are 150 mm thick

Table 3.4: Requirement of the Cement Used in Pavement Layers

Physical Properties	Obtained	Requirement as per IS:8112-2013
Initial setting time	140 minutes	30 minutes min.
Final setting time	400 minutes	600 minutes max.
Normal Consistency	28%	-
Compressive Strength (3, 7 &28 days)	28,36 and 45 MPa	23, 33 and 43 MPa
Fineness, m^2/kg	320	225
Soundness By Le Chatelier method, mm	2	10 max.
Chemical Properties	**Obtained**	**Requirement as per IS:8112-2013**
Ratio of percentage of lime to percentages of silica alumina and iron oxide $\frac{CaO - 0.7SO_3}{2.8SiO_3 + 1.2Al_2O_3 + 0.65Fe_2O_3}$	0.864	0.66-1.02
Ratio of percentage of alumina to that of iron oxide, Minimum	1.108	0.66
Magnesia, percentage of mass, maximum	4.47	5
Loss on ignition, percent by mass, Max	1.61	5
Total sulphur content calculated as sulphuric anhydride (SO3), percent by mass, Max	2.24	3.5

as opposed to 75 mm thick. Hence, it is advised that this layer be close to 100 mm thick. Additionally, instead of using the usual compaction test, layer compaction should be done using a 100% modified compaction method.

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